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16. ABSTRACT

Drinking water disinfection was shown to be an important public health measure around the turn of the century. In the United States, it was perhaps the single most important factor in controlling typhoid fever, a waterborne disease that was rampant throughout the world during the last century. It may also be assumed that disinfection was important in limiting the number of cases of other diseases known to be capable of waterborne transmission, i.e., cholera, amebiasis, shigellosis, salmonellosis, and hepatitis A. Even though modern treatment has eliminated water as a major vehicle of infectious disease transmission, outbreaks still occur. In fact, the annual number has been increasing since 1966. Interruption in chlorination or failure to achieve adequate levels of chlorine residual is the most often identified deficiency of the involved water supplies. This finding indicates that waterborne microbial pathogens remain as a potential health threat and underscores the importance of disinfection. From the outset, chlorination has been the drinking water disinfectant of choice in the country. Numerous studies have demonstrated its ability to inactivate bacterial, viral, and protozoal pathogens when applied uner proper conditions. However, the finding that chlorinated organics that are potentially carcinogenic are formed has prompted an evaluation of alternative disinfectants. The viable at alternatives to chlorine currently under consideration for widespread use are ozone, chlorine dioxide, and chloramines. In terms of biocidal efficiency, ozone is the most potent of the three. Chlorine dioxide is about the equivalent of free chlorine in the hypochlorous acid form but much more efficient than the hypochlorite form of free chlorine.

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Waterborne Outbreak Control: Which Disinfectant?

by Elmer W. Akin,* John C. Hoff† and Edwin C. Lippy*

Drinking water disinfection was shown to be an important public health measure around the turn of the century. In the United States, it was perhaps the single most important factor in controlling typhoid fever, a waterborne disease that was rampant throughout the world during the last century. It may also be assumed that disinfection was important in limiting the number of cases of other diseases known to be capable of waterborne transmission, i.e., cholera, amebiasis, shigellosis, salmonellosis, and hepatitis A.

Even though modern treatment has eliminated water as a major vehicle of infectious disease transmission, outbreaks still occur. In fact, the annual number has been increasing since 1966. Interruption in chlorination or failure to achieve adequate levels of chlorine residual is the most often identified deficiency of the involved water supplies. This finding indicates that waterborne microbial pathogens remain as a potential health threat and underscores the importance of disinfection.

From the outset, chlorination has been the drinking water disinfectant of choice in the country. Numerous studies have demonstrated its ability to inactivate bacterial, viral, and protozoal pathogens when applied under proper conditions. However, the finding that chlorinated organics that are potentially carcinogenic are formed has prompted an evaluation of alternative disinfectants. The viable alternatives to chlorine currently under consideration for widespread use are ozone, chlorine dioxide, and chloramines. In terms of biocidal efficiency, ozone is the most potent of the three. Chlorine dioxide is about the equivalent of free chlorine in the hypochlorous acid form but much more efficient than the hypochlorite form of free chlorine. The chloramines are weaker biocides than hypochlorite. Although this general order of ranking of efficiency holds for diverse types of microorganisms, quantitative comparisons vary with different microorganisms and experimental conditions.

Since the turn of the century, the benefits to public health from the disinfection of drinking water have been broadly recognized. The discovery that water could be a major vehicle of disease transmission preceded scientific verification of the germ theory of disease in the late 1800s. In 1854, John Snow made his classic deduction that a water supply was responsible for a severe cholera epidemic that was localized in a section of London, England. The outbreak that had caused 500 deaths was interrupted by removal of the handle on the Broad Street pump. A hint of the importance of water disinfection for disease control had actually been reported in 1835. *Human Health*, published in Philadelphia, stated that marsh water could be made potable by the addition of a small quantity of chlorine (*1*).

Concomitant with the recognition and acceptance of drinking water as a significant route of infectious disease transmission was the introduction of the disinfection process. In those early years, as now in this country, disinfection was synonymous with chlorination. In 1888, patents were issued on an

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electrolytic treatment process that generated chlorine from chloride of lime. The practice of chlorination of drinking water supplies spread throughout the major cities of the U.S. as the chlorine delivery process improved and experience revealed its microbial destructive power. It is interesting to note that the theory of chlorination chemistry that developed during the early 1900s indicated that nascent oxygen was responsible for the microbicidal action of the process. This theory, which also fostered interest in ozone as a disinfectant, was held until disproven in 1944 (*1*).

Waterborne Diseases

The most widely recognized achievement of drinking water treatment in the U.S. has been the dramatic reduction in typhoid fever which in large part is attributed to this single public health measure. The disease caused by an enteric bacterium was known to be waterborne with an estimated 40% of the cases attributed to this route of transmission. In 1900, the typhoid death rate in the U.S. had been 36 per 100,000 population, i.e., 25,000 deaths. As water treatment, including disinfection, became an increasingly common practice, the death rate decreased to 20 and 3 per 100,000 in 1910 and 1935, respectively. Perhaps Cincinnati's experience was typical. At the turn of the century, the city's water supply was the Ohio River with potability produced by only natural sedimentation to reduce settleable solids. The average annual typhoid fever illness rate during this time was almost 400 cases/100,000 persons. In 1907, the city added coagulation and rapid sand filtration treatment processes, and typhoid fever rates dropped precipitously. Chlorination, introduced in 1915, was followed by a second major reduction to a level less than one-tenth the rate reported for the year prior to introduction of water treatment (*2*).

Success in control of this disease by water treatment may better be illustrated by the decline in the reported cases of waterborne typhoid in the U.S. over the past 40 years (Fig. 1). In contrast to an annual average of 385 cases reported for the period 1940–45, no waterborne cases were reported during the 1976–79 period. A single typhoid outbreak resulting in 212 cases was responsible for increasing the annual average for 1971–75 from 2 to 44 cases. This outbreak resulted from the ingestion of contaminated ground water at a migrant work camp in Florida.

In addition to typhoid fever, other enteric pathogens have been associated with waterborne disease. The most widely recognized waterborne viral

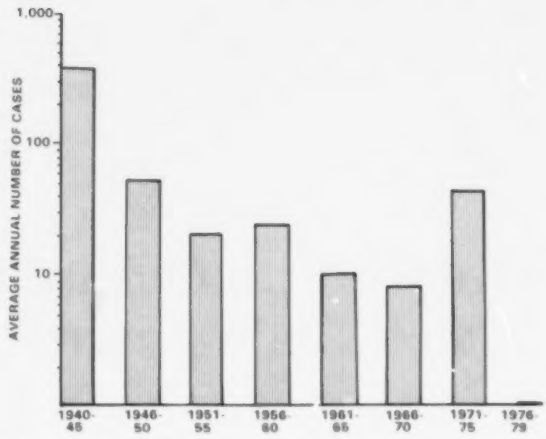

FIGURE 1. Average annual number of cases of typhoid fever in U.S. occurring in waterborne outbreaks from 1940 through 1979.

disease is hepatitis A. Mosley (*3*) compiled a list of 50 published reports worldwide of infectious hepatitis outbreaks attributed to contaminated drinking water. Epidemiological investigation has clearly shown this association even though disease manifestations normally do not appear until approximately 30 days after ingestion of contaminated water. Cholera and dysentery were rampant waterborne diseases during the 1800s but became less important in this century. Water disinfection most assuredly was important in their decline; however, the specific impact is not well documented.

Waterborne Outbreaks

Although the number of cases of waterborne infectious disease has been greatly reduced since the adoption of a standardized treatment process for unprotected surface water, outbreaks still occur. Actually, the annual number of reported outbreaks has been increasing since 1966 (Fig. 2). In 1979, the latest year for which complete data are available, 43 outbreaks were reported that resulted in 7,500 cases of illness. Preliminary information for 1980 shows a further increase in the number of cases. Outbreaks are reported on a voluntary basis to the Centers for Disease Control by state health agencies. Generally, there is not a concentrated effort to document occurrence of outbreaks and significant under-reporting is suspected. EPA is attempting to determine the actual occurrence of waterborne outbreaks through the support of studies in three states. The objectives are to design, implement, and evaluate a comprehensive surveillance system.

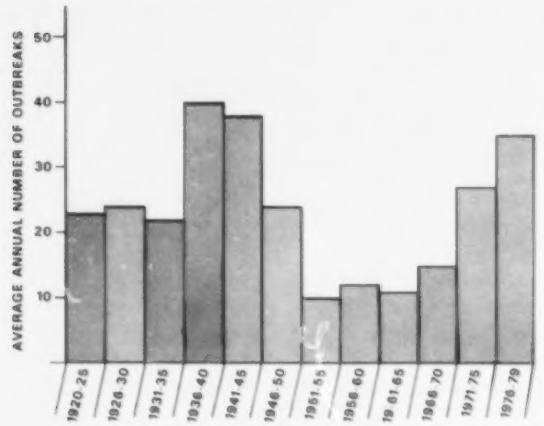

FIGURE 2. Average annual number of waterborne disease outbreaks occurring in U.S. from 1920 through 1979.

Investigations in one state uncovered seven outbreaks in the first 9 months of the study. In the previous year, only one outbreak had been reported through the normal surveillance procedures.

The most commonly occurring syndrome associated with waterborne illness is gastroenteritis that may be caused by a variety of microorganisms including viruses, bacteria, and protozoa. The frequency of each disease entity for outbreaks occurring between 1971 and 1977 is shown in Table 1. Acute gastrointestinal illness is a nonspecific category for which no known pathogens were identified. A group of viruses which have recently been observed by electron microscopy in the stools of outbreak victims is believed to be important in the etiology of this illness. Infectious hepatitis caused by hepatitis A virus is the most widely recognized waterborne virus illness. Epidemiological investigations have confirmed the waterborne transmission of this disease on numerous occasions. Since 1977, the protozoan *Giardia lamblia* has produced perhaps the largest number of waterborne disease cases and outbreaks. Its occurrence in "pristine" mountain streams contaminated by fecal waste of wild animals (especially beavers) has taken advantage of less vigorous water treatment procedures normally required for surface water sources (*4*). Inactivation of Giardia cysts requires more stringent control of the disinfection process than normally employed by many water utilities (*5*).

Conventional treatment, i.e., coagulation, sedimentation, filtration and chlorination, as it is commonly practiced in this country, coupled with an uncompromised distribution system, appears adequate to prevent waterborne infectious disease. However, the integrity of water systems is not assured and outbreaks are associated with breaches of these conditions. Table 2 indicates the causes of waterborne outbreaks in municipal and semipublic systems. Treatment deficiencies were important causes in both systems. Failure to maintain uninterrupted chlorination at an adequate chlorine concentration was found to be the single most important treatment deficiency (*6*). This was believed to be the cause of a recent gastroenteritis outbreak associated with a groundwater supply in a Texas community that affected approximateiy 8000 residents. The symptoms, i.e., rapid onset of diarrhea and abdominal cramps accompanied by headache and nausea, were typical of enteric microbial disease. However, no etiological agent has yet been identified. About 30 cases of hepatitis A were also associated with this outbreak (Lippy, unpublished data).

Table 1. Etiology of waterborne disease outbreaks in the U.S., 1971-1977.[a]

Type of illness	Outbreaks, %	Cases of illness, %
Acute gastrointestinal illness	57	58
Chemical poisoning	12	3
Giardiasis	10	18
Shigellosis	9	14
Hepatitis A	8	1
Salmonellosis	2	3
Typhoid	2	<1
Enterotoxigenic *E. coli*	<1	3
	100	100

[a]Data of Craun (*6*).

Water Disinfection

Although virus isolations from disinfected drinking water have been reported (*7*), most health authorities believe that chlorination, when prac-

Table 2. Waterborne disease outbreaks in the U.S., 1971-1977: type and deficiencies of water systems.[a]

Deficiency	Percent of outbreaks	
	Municipal systems	Semipublic systems
Untreated surface water[b]	14	9
Untreated ground water	10	43
Treatment deficiencies	28	40
Distribution deficiencies	40	2
Miscellaneous	8	6
	100	100

[a]Data from Craun (*6*).
[b]Includes giardiasis outbreaks in chlorinated, but not filtered, systems.

ticed under recommended conditions, is adequate for preventing the transmission of pathogens through drinking water. The current widespread use of free residual chlorine for disinfection of drinking water evolved as a result of developments in our knowledge of chlorination chemistry and the biocidal capabilities of various forms of chlorine. Early water chlorination practice was termed simple chlorination or marginal chlorination. It consisted of adding chlorine as a final step after filtration or the use of chlorine as the only treatment. In the early 1900s, observations indicating that bactericidal action continued even after free chlorine had disappeared, and the subsequent discovery that the combined chlorine products formed also had disinfecting capabilities led to the widespread use of chloramines. In part, this change was made because the use of chloramines eliminated the tastes and odors caused by the reactions of free chlorine with phenols and other organic compounds. Later, recognition of the superior biocidal capabilities of the hypochlorous acid form of free residual chlorine and development of the "breakpoint" concept resulted in changing to the current predominant practice of free residual chlorination.

During this period, a great variety of physical and chemical agents have been studied regarding their potential utility for water disinfection. Some, such as heat, are highly effective, but impractical because of cost. Others may be unsuitable because their effects are selective, e.g., quaternary ammonium compounds are effective bactericides, but ineffective viricides. Chemical oxidants are the most widely used and potentially usable agents. These include the halogens such as bromine, iodine, and chlorine in various forms, metal salts such as ferrate and permanganate, and peroxides such as ozone and hydrogen peroxide. Of these, only ozone, chlorine dioxide and chloramines are currently considered to be immediately viable alternatives to free residual chlorine for use as primary disinfectants for potable water. This consideration is based mainly on the fact that these agents have been used successfully in actual treatment practice. The use of chloramines in some treatment systems has continued, with apparent success, in spite of laboratory data indicating that they are relatively poor disinfectants.

Comparative Biocidal Efficiency

The assessment of the biocidal efficiency of disinfectants is based mainly on the results of laboratory experiments conducted under controlled conditions. Some of the problems associated with such assessments were described by Morris (*8*) as follows:

> "Although the bases for the quantitative expression of the effectiveness of germicidal agents have been known for more than 60 years, there has been relatively little application to the systematic tabulation of the relative potencies of disinfectants. Only a very small fraction of the total published literature on germicidal action is sufficiently complete or in form suitable for satisfactory quantitative analysis. Moreover, there is no consensus on which method of tabulation is most convenient. Probably the most common technique is to list the concentrations required to give a fixed percentage of kill with a given time of contact, but there is no unanimity with regard to either the percentage or the time."

Inactivation of microorganisms by chemical disinfectants can be considered as a first-order chemical reaction in which the rate of inactivation is dependent on the disinfectant type and species, the disinfectant concentration, and the microorganisms being inactivated. Although actual data often show deviation from first-order kinetics, it is a useful concept. Using data in this way, comparative biocidal efficiency can be expressed as the relative concentration of various disinfectants required for equivalent disinfection rates or as the relative inactivation rates produced by equivalent concentrations of different agents. Data from laboratory experiments conducted at constant disinfectant levels and with pure cultures of the organism are shown in Figures 3 and 4. The data shown are composites of results from studies conducted over a period of years in one laboratory using consistent experimental methods and microorganism strains (*9*).

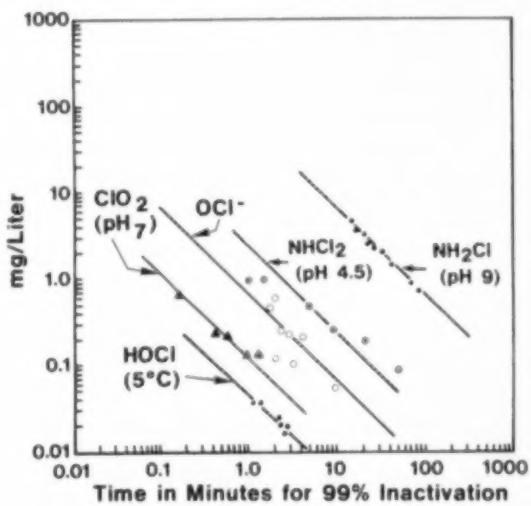

FIGURE 3. Inactivation of *E. coli* (ATCC 11229) by free and combined chlorine species and chlorine dioxide at 15°C (*9*, *13*).

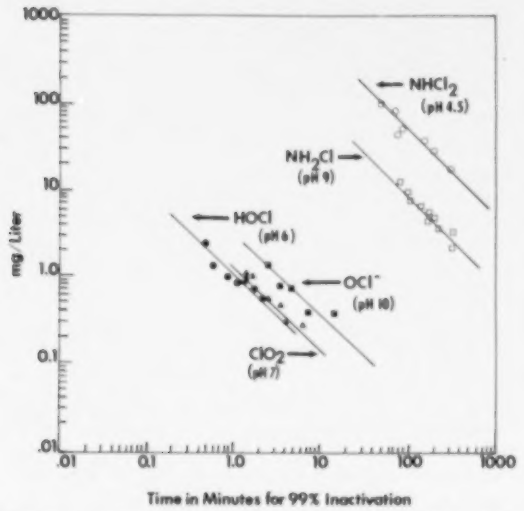

FIGURE 4. Inactivation of poliovirus 1 by free and combined chlorine species and chlorine dioxide at 15°C (*9*, *13*).

Figure 3 shows the times and concentrations of several disinfectants required to cause inactivation of 99% of a population of *Escherichia coli*. Free residual chlorine in the form of hypochlorous acid is somewhat more effective than chlorine dioxide, but in its other form, hypochlorite ion, free residual chlorine is less effective than chlorine dioxide. Dichloramine is somewhat less effective than hypochlorite ion and monochloramine is the least effective. The overall pattern shown by results of studies of poliovirus 1 inactivation (Fig. 4) is similar. Note that all of the curves are further to the right, indicating the generally higher resistance pattern of viruses than *E. coli* to the disinfectants. Hypochlorous acid and chlorine dioxide are similar in efficiency with hypochlorite ion somewhat less effective. Both chloramine species are much less effective, but their order of efficiency is reversed from that shown for *E. coli*. Studies similar to these with ozone are difficult because the instability and extremely rapid inactivation rates shown by this disinfectant make it difficult to obtain reproducible results. Studies that have been done indicate that ozone is perhaps two to three orders of magnitude more efficient than free residual chlorine (*10*, *11*). The overall efficiency rankings indicated in Figures 3 and 4 are consistent in general with the disinfection literature for all microorganisms including bacteria, viruses and protozoan cysts. However, precise quantitative ranking of the disinfectants with regard to the degree of difference in efficiency is not possible.

Water pH has important effects on the efficiency of free residual chlorine and chlorine dioxide. In the case of free residual chlorine, increasing the pH from 6 to 10 alters the disinfectant species present from a very efficient nonionized chemical species to a much less efficient ionized species. In contrast, the efficiency of chlorine dioxide increases over a similar pH range. Both *E. coli* (*12*) and poliovirus 1 (*13*) are inactivated more rapidly at pH 9 than at pH 7 by chlorine dioxide. In this case it appears to be a change in the sensitivity of the organisms since chlorine dioxide remains the same chemically over this pH range. Further evidence that different microorganisms are affected differently by disinfectants is shown in Table 3 (*14*). This group of six enteroviruses show widely differing patterns of resistance to both hypochlorous acid and hypochlorite ion. Relative differences in resistance to hypochlorous acid and hypochlorite ion range from 5-fold to 192-fold for different enteroviruses. In the same study, they showed that the presence of an inorganic salt (KCl) can significantly influence the rate of inactivation of viruses by both free chlorine species. Others have confirmed this observation and have shown that similar effects are produced by NaCl and CsCl (*15–17*). More recently, Haas and Zapatkin have shown that *E. coli* is similarly affected (*18*).

Choosing a Disinfectant

The important considerations in choosing a disinfectant appear to be technical rather than economic in nature. Cost comparisons have not been presented here. However, Clark (*2*) has determined that while operating cost of using the disinfectants under discussion may vary 3- to 4-fold, when considered in terms of cost-benefit ratios, all three show a highly positive net benefit.

An important consideration in choosing a disinfectant for use in water treatment is the stability of the disinfectant species. In general, degree of

Table 3. Comparison of virus inactivation by free residual chlorine at pH 6.0 and 10.0, and 5.0°C ± 0.2°C.[a]

Virus strain	Time for 99% inactivation, min		
	pH 6.0	pH 10.0	Ratio[b]
Coxsackie A9 (Griggs)	0.3	1.5	5
Echo 2 (Farouk)	0.5	96.0	192
Polio 2 (Lansing)	1.2	64.0	53
Echo 5 (Noyce)	1.3	27.0	21
Polio 1 (Mahoney)	2.1	21.0	10
Coxsackie B5 (Faulkner)	3.4	66.0	19

[a]Data of Engelbrecht et al. (*14*).
[b]Time required at pH 10.0/time required at pH 6.0.

Table 4. Summary of disinfectant characteristics relating to biocidal efficiency.

Disinfectant	Rank[b]		pH effects on efficiency (pH range 6–9)
	Biocidal efficiency	Stability	
Ozone	1	4	Little effect
Chlorine dioxide[c]	2	2	pH increase is beneficial
Free chlorine[c]	3	3	pH increase is detrimental
Chloramines	4	1	Little effect

[a]Data of Hoff and Geldreich (*19*).
[b]1 = best, 4 = worst.
[c]Ranking influenced by pH

stability correlates inversely with biocidal efficiency, the more stable the disinfectant, the less efficient. Although chlorine dioxide is similar in disinfection capability to hypochlorous acid, it is considered to be more stable because it does not react with ammonia which is frequently present in raw waters. However, disinfectant stability can also be considered beneficial because stable disinfectants such as chloramines, although less efficient, may be very effective because of their prolonged persistence. An overall view of some of the characteristics of ozone, chlorine dioxide, and free and combined chlorine is shown in Table 4. It is clear that none of the agents is optimal in all respects. The current concern regarding disinfection and the production of potentially toxic substances, the subject of this symposium, further complicates this picture. Perhaps the only firm conclusion that can currently be drawn concerning drinking water disinfection is its absolute requirement, by some means, in the treatment process if the transmission of waterborne infectious disease is to be prevented.

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